APPLICATION OF AN ADAPTIVE CONTROL GRID INTERPOLATION TECHNIQUE TO MORPHOLOGICAL VASCULAR RECONSTRUCTION: A COMPONENT OF A COMPREHENSIVE SURGICAL PLANNING AND EVALUATION TOOL

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Abstract – **The total cavopulmonary connection (TCPC) is a palliative surgical repair performed on children with a single ventricle (SV) physiology. Much of the power produced by the resultant single ventricle pump is consumed in the systemic circulation. Consequently the minimization of power loss in the TCPC is imperative for optimal surgical outcome. As a component of a comprehensive surgical planning and evaluation tool we have developed a method of vascular morphology reconstruction based on adaptive control grid interpolation to function as a precursor to computational fluid dynamics (CFD) analysis aimed at quantifying power loss. Our technique combines positive aspects of optical flow-based and block-based motion estimation algorithms to accurately reconstruct vascular geometries with a minimal degree of computational complexity. Subsequent CFD simulations offer the pressure and velocity information necessary to quantify power loss in the TCPC on a pre and post-operative basis. Collectively these steps form a powerful tool for both surgical planning and evaluation aimed at producing optimal TCPC configurations for successful surgical outcomes. Both reconstruction and CFD components of the technique will be discussed.**

***Keywords* – Reconstruction, computational fluid dynamics (CFD), total cavopulmonary connection (TCPC)**

I. Introduction

The total cavopulmonary connection (TCPC) is a palliative surgical repair performed on children born with single ventricle (SV) physiology. Children with such physiology have a mixing of oxygenated and deoxygenated blood, which when left untreated leads to inadequate tissue oxygenation and cyanosis. In order to prevent systemic and pulmonary blood from mixing, the surgeon will disconnect the pulmonary artery from its ventricular origin, anastomose the superior vena cava to the unbranched right pulmonary artery (RPA), and construct a lateral tunnel through the right atrium connecting the inferior vena cava with the RPA. The procedure results in a complete bypass of the right heart with the single ventricle driving blood through the entire circulatory system.

Much of the power produced by the single ventricle pump is consumed in the systemic circulation. For this reason minimizing and monitoring power loss in the modified district is critical for optimal surgical outcomes. Presently, the surgeon's experience dictates the implemented intervention with little attention paid to achieving minimal power loss. To refocus connection choice on fluid dynamics, our group is developing surgical planning techniques for the TCPC. Such techniques will aid the surgeon in selecting the optimal TCPC among possible alternatives for specific patients. The proposed methodology employs combined use of magnetic resonance (MR) imaging and computational fluid dynamics (CFD) to study flow conditions among alternative post-operative morphologies prior to performing the surgical procedure. First MR images containing anatomical information will be acquired and used to reconstruct morphological models of pre-operative anatomy. Next, the surgeon and engineers collaboratively construct computer models of possible connections within the framework of the pre-operative reconstructions. Finally computer simulations are performed for each connection alternative to provide pressure, flow, and power loss information thereby allowing the surgeon to select the best alternative. In addition the detailed velocity information generated by CFD can be utilized in the pre-operative scenario to predict the occurrence of longer-term problems such as thromboembolic episodes and flow induced vascular damage.

Before the CFD-based planning technique can be implemented in the clinical setting, it must be validated using MR scans from previous TCPC recipients. In these post-operative cases, power loss estimations from CFD evaluations are obtained from reconstructions following TCPC surgery. Power losses computed from CFD can be compared directly with those obtained using the dissipation function method based on MR velocity measurements [1].

In order to execute CFD simulations at any stage, comprehensive three-dimensional anatomical information is required. Volumetric morphological MR imaging methods extract high quality information, but demand excessive acquisition time even for relatively small volumes. Our reconstruction method is an alternative that provides the desired information without exorbitant scan time. By using a series of two-dimensional morphological MR images we are able to reconstruct an accurate geometry which can then be analyzed using CFD. Reconstruction from a series of images necessitates the approximation of data contained in the original three-dimensional structure, but not captured with two-dimensional imaging. Numerous methods of

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Abstract

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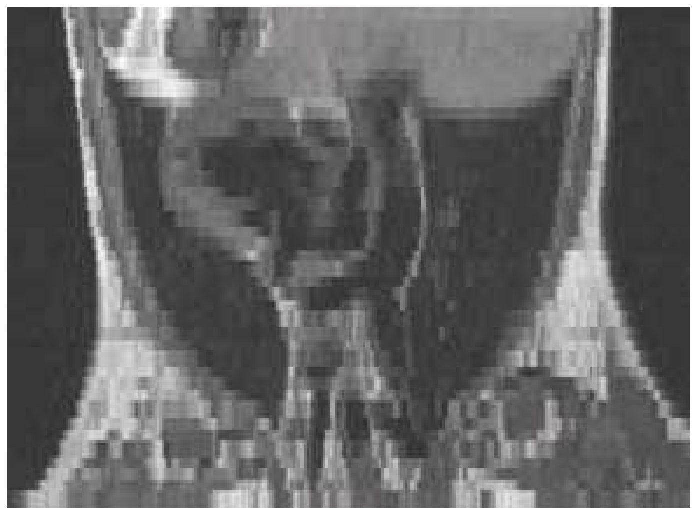
interpolation have been proposed to accomplish this task [2]. Reconstruction methods customarily require a method for establishing a correlation between points in related images as a precursor to interpolation. We have developed a new technique to accomplish this task, whereby a modified form of control grid interpolation (CGI) is used to calculate vectors that describe pixel movement [3-5]. This technique provides us with an accurate morphological reconstruction suitable for importation into CFD software. This can be carried out both as a precursor to the actual operation, serving as a starting point for surgical simulations and subsequent determination of optimal TCPC configurations, and as a means of conducting post-operative evaluation of power loss based on generated pressure data and long term factors based on generated velocity data.

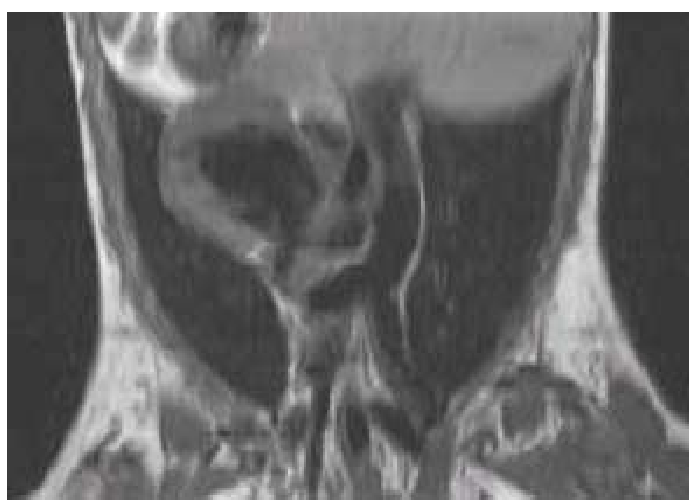
II. Methodology

The starting point for our reconstruction process is a series of transverse modulus MR images taken at uniformly spaced depths through a patient's chest. Fields of motion vectors are then calculated describing the displacement of pixels from one modulus image to another. In the CGI representation, the motion field is obtained by segmenting the image into contiguous rectangular regions. The corners of these regions form control points that are used as the anchors from which the motion vectors in between are derived via bilinear interpolation. In contrast to traditional block matching approaches, which are commonly used for motion vector estimation, CGI is attractive for this application because it allows for the representation of complex non-translational motion. In this work we employ an adaptive CGI algorithm to partition the image into sub-blocks of size sufficient to capture characteristics of complex anatomical transition. In addition, we employ optical flow equations to calculate the motion of the CGI control points instead of an iterative search-based method. These characteristics of the algorithm are important, since we wish to obtain an accurate and dense representation of the field of motion vectors at a minimal cost in terms of computational complexity.

The first pass of this motion vector calculation algorithm yields the best approximation of a control point pixel's destination on the dense grid of dimension determined by the MR scan. Following this portion of the technique a recursive interpolation scheme is employed to further increase the accuracy of each motion vector to a specified degree. Assuming that the actual destination of a given pixel lies somehwere between the best approximation on the dense grid and one of it's surrounding neighbors, the search region is pinpointed. Interpolants are then interleaved between the members of this nine pixel neighborhood until a motion solution decreasing error below the specified threshold is located. In doing this an arbitrary degree of sub pixel accuracy is incorporated into the routine. As a result of the completion of this process for each control point, and the aformentioned bilinear interpolation, a dense field of motion vectors is obtained. By following one of these vectors a portion of the way from one image to the next, a linear approximation of where a given pixel would be found in an intermediate image can be made. Repeating this process for an entire image yields an interpolated intermediate image between two known images. Pairs of these images are then combined in a spatially weighted sum to form a single interpolated frame. This process is then repeated and several interpolated images are stacked between the known images in physiologic proportion to produce a three-dimensional augmented data set. A coronal view of an augmented data set is displayed in Fig. 1 along with the original. Each frame is then segmented with a semi-automated segmentation routine prior to reconstruction.



Original



Augmented

Fig. 1. Coronal view of original and augmented MR data sets.

The interpolation process can be performed using modulus images to reconstruct morphology as it is in this application, or phase encoded images to reconstruct a flow field. As a result of the smooth variance of the TCPC vasculature, one might propose that interpolation along any vector would be sufficient to reconstruct an accurate morphology. The appeal of using the adaptive CGI technique to arrive at vectors to interpolate upon is that because of its sensitivity to both intensity and gradient information and its ability to detect complex non-translational motion, this method is especially adept at creating interpolation vectors that reconstruct accurate data near vessel boundaries. This point is extremely important for reconstructions to be used as CFD models for quantitative analysis of flow characteristics.

The reconstructed TCPC geometry is then imported into a CFD preprocessor for discretization of the flow domain. Fidap version 8.5 (Fluent, Inc., Lebanon, NH), a finite element based CFD software, is used to solve the equations of mass and momentum conservation. The use of a finite element based code is important due to the complexity and irregularity of the reconstructed TCPC's geometry. Such a code allows for an unstructured mesh and thus discretization of the flow domain can be generated with greater ease and less user input. Furthermore, finite element based software allows for the simulation of fluid-structure interaction, which can be beneficial for investigating energy losses associated with using various types of native and artificial graft materials in completing the surgical connection.

Uniform velocity boundary conditions, obtained from MR flow measurments, are imposed at the model's inlets and specific pressure boundary conditions are imposed at the model's outlets to obtain the physiologic pulmonary flow split determined from MRI flow measurements. A no slip boundary condition is enforced along the rigid, vessel wall, and the blood flow is assumed be steady, laminar, incompressible, and newtonian. Lastly, TCPC power losses are determined using an intergral formulation of the control volume method.

III. Results and discussion

In order to validate the reconstruction portion of our technique, numerical models of TCPC phantoms were examined. Planes from these phantoms were extracted, blurred in a Gaussian fashion, and then distorted with noise to simulate MR images. These simulated images were then reconstructed using three different interpolation techniques: linear, spline, and ACGI. Reconstructions affirmed that the ACGI technique did in fact reconstruct with a greater degree of accuracy as shown in Fig. 2.

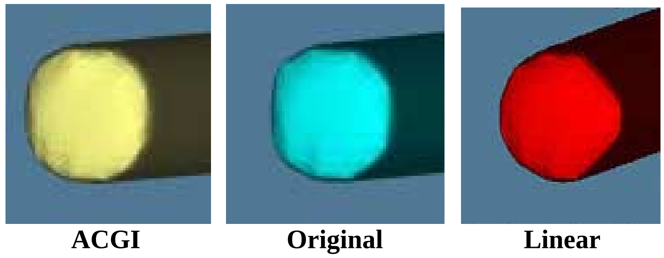


Fig. 2. View of reconstruction cross sections.

Simple in vitro phantom models were also constructed to aid in validating the reconstruction algorithm. These glass pipe intersection models were scanned and the reconstruction process was then applied to the acquired data set. The morphological reconstructions displayed dimensions that differed from the original in vitro model by less than six percent by volume and less than four percent by diameter at any cross-section of the pipe. These results together affirm that our technique can use non-invasively obtained data to reconstruct accurate comprehensive information about patient vasculature for quantitative flow analysis. Following this validation, data sets from patients having a surgically created TCPC were used in reconstruction. One such three-dimensional reconstructions is displayed in Fig. 3. The unstructured CFD mesh created from this reconstruction is displayed in Fig. 4.

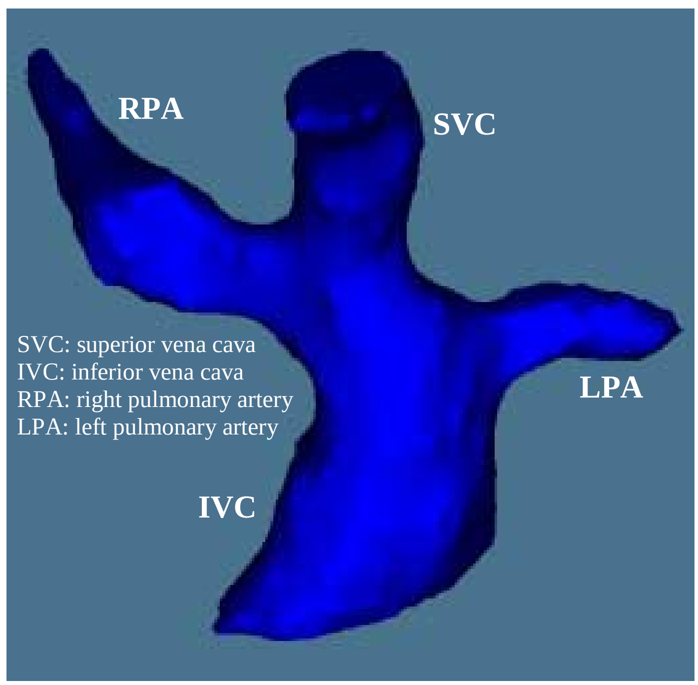


Fig. 3. Example of patient TCPC reconstruction.

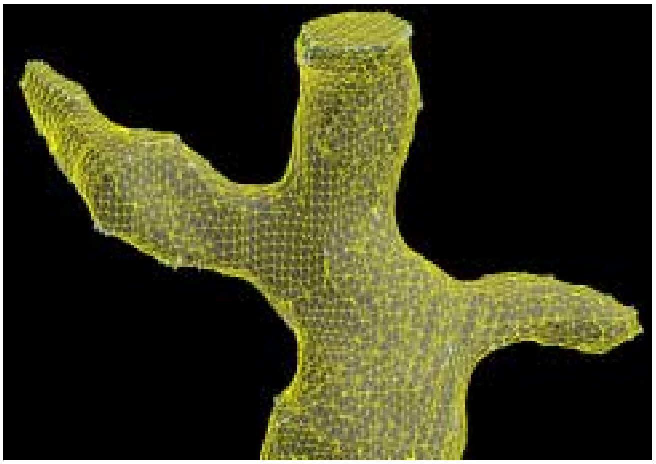


Fig. 4. Tetrahedral mesh topology of TCPC.

Currently, CFD simulations have been performed on idealized models of the TCPC. Two models have been investigated to study the effects of vessel size and three-dimensional vascular structure on the energetic efficiency of the connection. The first model retained the planar arrangement of all vessels involved in the TCPC, but vascular diameters were selected to mimic physiologic sizes resulting in a matched-diameter model. The second model consisted of constant-vessel diameters with non-planar features producing a matched-planarity model. Power losses obtained from these two altered models were compared to power losses obtained from the simplified TCPC model used in previous studies. Using the integral control volume assessment, power losses in the matched-diameter and matched-planarity models exceeded those obtained from the simplified model. These results show that simplifying assumptions applied to TCPC geometries produces a significant impact on the computed power losses. This is a driving factor for using computational models reconstructed from MR images obtained from TCPC recipients in the search for improved TCPC designs.

IV. Conclusion

Effective analysis of TCPC performance requires comprehensive three-dimensional pressure and/or velocity information. Due to the difficulty associated with extracting such data in vivo, and the surgical planning context within which that data are ultimately to be used, CFD has been selected as an attractive alternative data acquisition method. Our technique employs ACGI to reconstruct morphological information as a necessary precursor to CFD analysis. By combining advantages of block-based and optical flow-based motion models, correlations are established between related images leading to physiologically realistic interpolated data. Results have shown that this reconstruction technique can be carried out using data acquired in a fraction of the time required by volumetric data acquisition methods, while providing accurate three-dimensional information for CFD. CFD simulations then yield the data needed to carry out power loss calculations. This gives us the ability to examine different types of TCPC configurations both pre and post-operatively in order to determine characterisitics contributing to optimal patient outcome.

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